Munn, Robert Edward
The indentification of early indicators of CO_2 climate warming in Canada

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The Identification of Early Indicators of CO_2 Climate Warming in Canada

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The Identification of Early Indicators of CO_2 Climate Warming in Canada

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Summary

Concentrations of CO_2 and other greenhouse gases are increasing, and this trend is likely to continue for at least the next 50 years. The resulting global warming predicted to occur would have significant socioeconomic consequences for Canada. It is therefore important to identify the components/elements of climate-related monitoring systems that would provide very early indications of a warming trend. That is the central theme of this report.

After a general discussion in Section 2 on early detection of climate change, a general description is given in Section 3 of the various statistical methods available. The recommendations contained in two United States and one WMO report on climate change are reviewed in Section 4, laying the foundation for the discussion in Section 5 of appropriate indicators of climate change in Canada. Finally, there is a brief discussion of the problem of estimating the length of time that a trend would have to continue before it could be distinguished from a short-term climatic anomaly.

The main recommendations are drawn together in Sections 8.1 to 8.6 inclusive. The most important ones are that:

(a) Canada should continue to support the efforts of the WMO/ICSU World Climate Programme in this area.

(b) The following priority early indicators of climate change are recommended: surface, tropospheric and stratospheric temperatures and thicknesses; downward short-wave and long-wave radiation; cryosphere indicators; aerosol extinction; water temperature in the Bay of Fundy.

(c) The Canadian Climate Centre should establish a Working Group to develop a set of indicators of the characteristics of the general circulation to aid in the interpretation of time series of early-warming indicators.

(d) A careful study should be made of the representativeness and homogeneity of Canadian climate stations and data. Arctic and subarctic stations should not be excluded from this examination even though the length of record is relatively short in many cases.

(e) The Box-Jenkins intervention technique is recommended for trend detection but other methods should also be used and results should be compared.

(f) Signal-to-noise ratios should be estimated to establish priorities amongst different kinds of indicators and amongst various sites.

(g) A Workshop to elaborate some of the ideas contained in this Report might be a useful step forward in late 1985 or 1986.

1. Introduction

The possibility of CO_2 climate warming is a major environmental issue of the present decade. This is particularly so with respect to the sub-arctic and arctic where CO_2 warming is predicted to be greatest.

Atmospheric concentrations of CO_2 have been increasing since the last century and they will continue to rise for at least the next 50 years. At the same time, concentrations of other gases (e.g., the chlorofluoromethanes, carbon monoxide, methane and nitrous oxide) with "greenhouse" characteristics are increasing. The resulting effect on the radiation balance of the atmosphere is reasonably well understood; viz., cooling of the upper stratosphere and warming of the troposphere. However, long-term climatic predictions are very uncertain for several reasons. In the first place, a changed radiation balance would change the general circulation of the atmosphere, affecting wind, cloud and precipitation patterns. Current simulation models, although enormously complex in some cases, contain only very crude representations of some important atmospheric processes. Secondly, the models generally provide only long-term steady-state solutions whereas transient responses to a rise in CO_2 concentrations might be quite different (Weller _et al_., 1983, pg. 308). Thirdly, events such as intense volcanic eruptions might slow down or even reverse the warming trend.

Turning to the subject matter of this report, the main topic to be considered is the early detection of climate warming. How will Canadians know that an upward trend has really begun? Has global warming already begun? This is in fact a very difficult question to answer because of the great natural variability in weather and climate from place to place and from year to year. Fig. 1-1 shows global trends since 1880, and even with 5-year running means and longitudinal averaging, there is still considerable variability (Hansen _et al_., 1983).

To be more specific, the objectives of the report are as follows:

1. To describe the factors that must be considered when searching for early signs of climate change (Section 2);

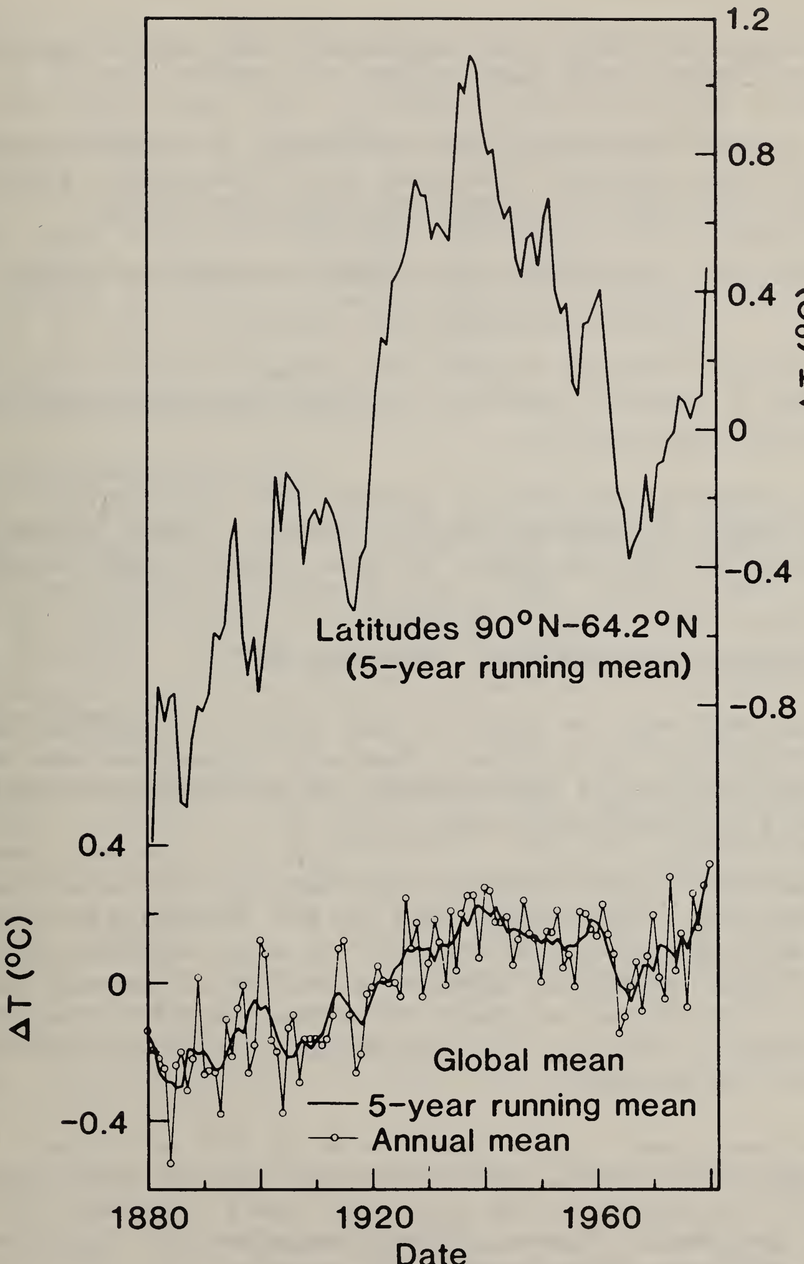

Fig. 1-1: Observed temperature trends. (Hansen et al., 1983)

2. To describe statistical approaches that may be applied to detect climate trend (Section 3);

3. To discuss various global indicators of climate warming that have been proposed (Section 4); (Presumably global trends should be easier to detect than national ones.)

4. To discuss indicators of climate warming in Canada (Section 5);

5. To review existing climate and climate-related monitoring networks in terms of their utility for early detection of climate warming (Section 6);

6. To recommend statistical methods for determining in advance, the length of record required to detect trends of various magnitudes at various levels of statistical significance (Section 7);

7. To make recommendations. (Section 8).

No attempt will be made in this report to analyse data or to carry out feasibility studies. However, recommendations concerning future work priorities with respect to early detection of climate change will be made (Section 8).

There are several reasons for seeking indicators of climate change and for formulating appropriate statistical methods for testing the significance of trends. Of most importance is the need that may arise to decide whether a string of unusual winters or summers is sufficient evidence to warrant modification of current socio-economic practices for managing climatologically-sensitive sectors of the economy.

A second reason is to avoid bias in the selection of statistical significance tests that might be used at some future date. Otherwise, the nature of the data sets could influence the types of analyses performed. Epstein (1982) remarks that "hypotheses to be tested in the future should be stated now."

A third reason relates to the fact that renewable resources are interconnected on continental and even global scales. It is therefore important that differences amongst countries with respect to perceptions of climate trends be made explicit. After a series of droughty summers, for example, international tensions with respect to food policies could arise if some nations felt that a new climate regime had started while other nations believed that the anomalous weather would soon end.

Lastly, there is the Canadian public which has a continuing interest in climate change; far better that the information distributed by the media come from informed Canadian sources rather than from a U.S. wire service or a BBC television production.

Finally in this introduction it should be mentioned that there is a very wide array of possible indicators of climate change. Appendix 1 lists elements usually considered to be climatic or climate-related, but only a few of these are likely to be of practical value as early indicators of greenhouse warming.

2. Some General Considerations

2.1 The published literature

Many papers have been published on the subject of early detection of CO_2 climate warming. Of most value are the review articles by Klein in the Carbon Dioxide Review: 1982 (Clark, 1982, pp. 215-242) and by Weller *et al.* in Changing Climate (Nat. Acad. Sci., 1983, pp. 292-382). An international perspective is provided by a WMO/ICSU Report of a Meeting on Detection of Possible Climate Change (WCP, 1982).

Because trend analysis is an important issue in environmental fields, the technical literature on the subject is scattered through many journals and disciplines. In this connection, early detection of change in wet deposition of sulphur following a change in regional emissions of SO_2 is the subject of a recent Workshop report (Munn, 1984). Some useful analogies exist between the SO_2 and the CO_2 question, although the latter problem is more complex (more feedbacks, more indicator variables and larger space scales).

These various literature sources have been useful in the preparation of this report.

2.2 Representativeness and homogeneity of climate data sets

In this and following subsections, we shall discuss some of the factors that must be taken into account when searching for climate change. First is the question of the representativeness of monitoring sites, which are subject to:

(a) micrometeorological influences; (If a Stevenson screen is moved a hundred metres or so, for example, there could be an important discontinuity in the temperature measurements.)

(b) mesometeorological influences; (A station such as Toronto Bloor Street has been gradually warming over the last decade due to increasing urbanization.)

(c) macrometeorological influences. (This is the scale of interest with respect to CO_2 climate warming.)

As an example of a mesoscale influence, Fig. 2-1 gives 5-year running mean winter temperatures at Toronto Bloor Street and at Beatrice, Ont., as well as their differences (Aston, 1984). The Beatrice climatological observing station is located between Bracebridge and Huntsville, and has remained rural over the last century (AES, 1975). Fig. 2-1 reveals rather large decade-by-decade oscillations in winter temperature at both sites (a range of more than 4°C over the last century); however, oscillations in temperature differences (lowest curve) are much smaller, indicating that the two stations are subject to many of the same large-scale influences. An additional point of interest is that the difference curve shows an upward trend. Over the last 100 years, the temperature at Toronto Bloor street has increased by about 2°C relative to Beatrice due to the growth of the city. In this connection, it is of interest to mention a study of climate change by Madden and Ramanathan (1980) in which 72 years of data from 12 stations circling the globe at about 60N were used to calculate temperature variance. The three Canadian stations included were Edmonton, Winnipeg and Moosonee, two of which are in urban environments! (The variances of time series are inflated by the presence of trend.)

An equally important consideration in trend analysis is homogeneity with respect to instrumentation and observing procedures. A change in the type of instrument used, height of exposure above ground or observation times, e.g., of rawinsonde flights, could introduce significant inhomogeneities. (See WCP, 1982, pg. 9, for example.)

2.3 Climate variability

Climate varies in time and space. An indication of the degree of time variability in annual mean temperature was given in Fig. 1-1. Additional information is provided in Fig. 2-2, which presents time series of temperatures by season for the arctic and subarctic (Raper *et al*., 1983). Fig 2-2 shows that recent warming in the Northern Hemisphere has been a winter-time phenomenon. In particular, the winter of 1980-81 was the warmest over the period displayed, i.e., back to 1881 (Wigley *et al*., 1981). Figs. 1-1 and 2-2 are based on hemispheric values. For data averaged over a small region, and even more so for time series from individual

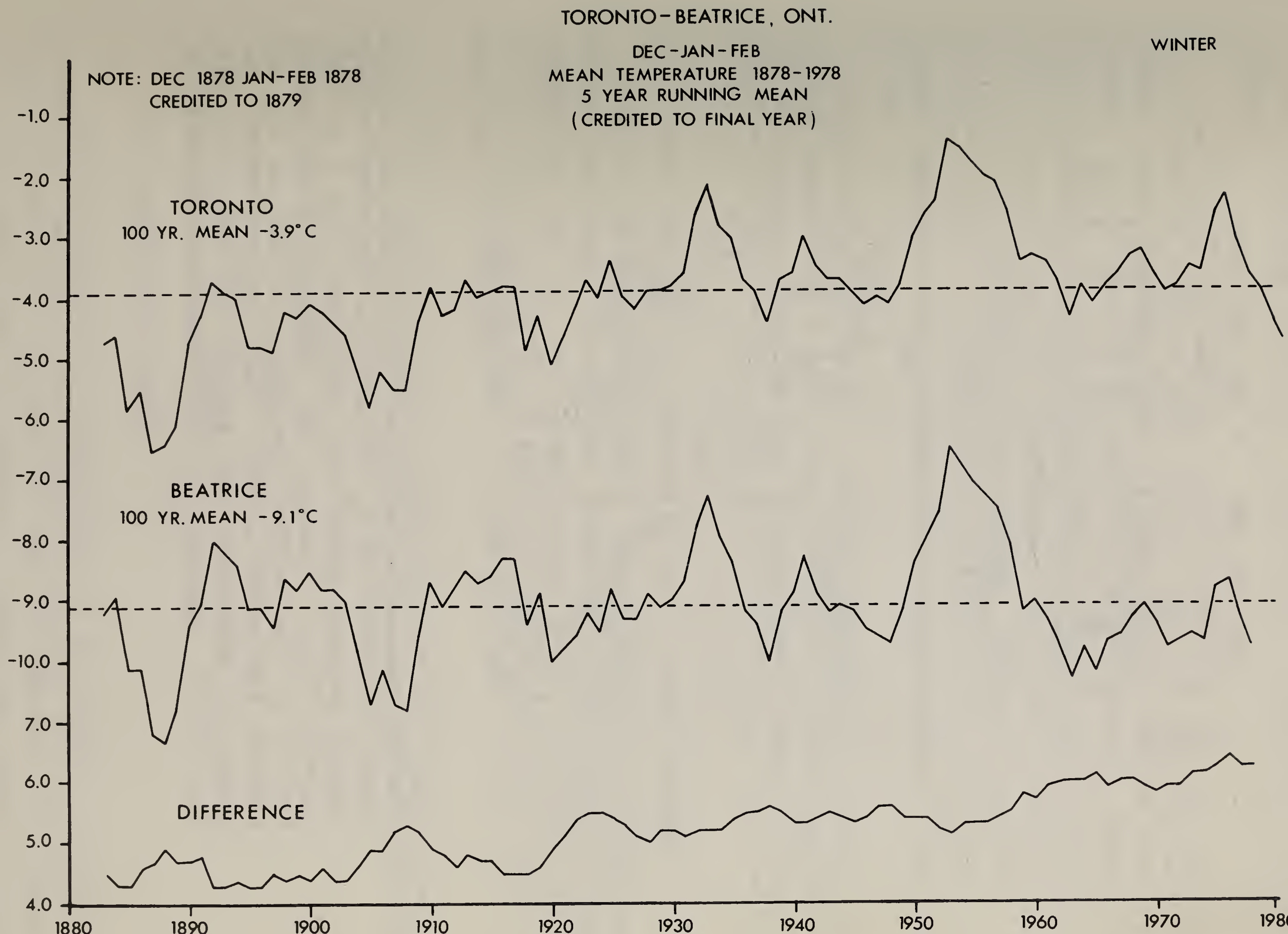

Fig. 2-1: (Aston, 1984).

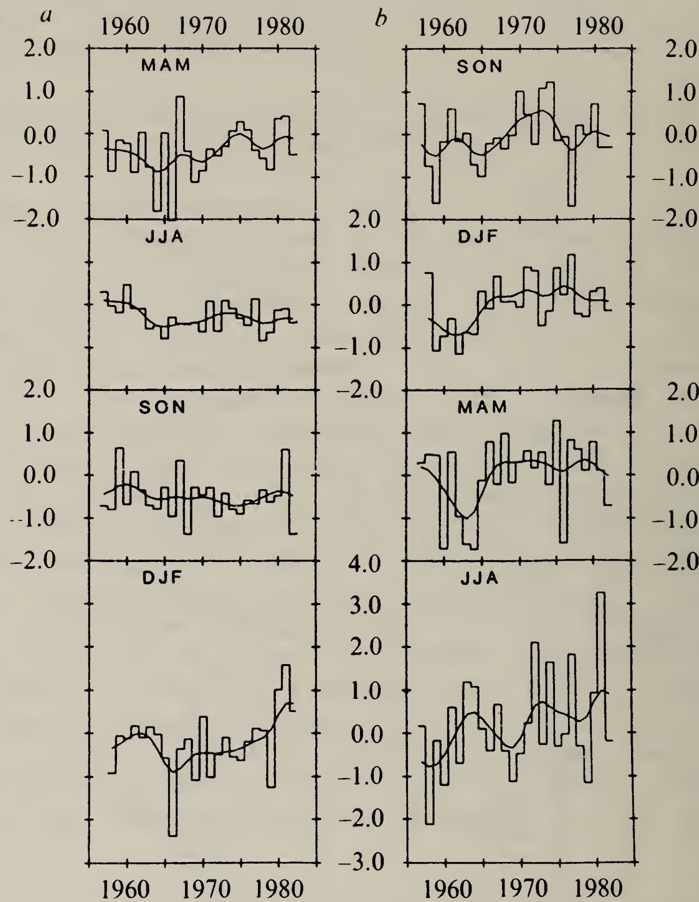

Fig. 2-2: Seasonal temperature anomalies (°C) averaged over a, the Arctic (65-90°N); and b, the Antarctic (65-90°S). Superimposed smoothed values were calculated using a 9-weight binomial filter. Seasons are identified by the months (spring for the Northern Hemisphere is MAM and for the Southern Hemisphere is SON). (Raper et al., 1983). Reprinted by permission from Nature, Vol. 306, No. 5942, pp. 458-459. Copyright (c) 1983, Macmillan Journals Ltd.

weather observing stations, inter-annual variability will be larger.

The reason that climate varies from year to year and from place to place is to be found in the "internal complexities of the global climate system" (Raper et al., 1983). In some years, the general circulation may be considerably stronger (or weaker) than average and/or the long-wave troughs and Southern Oscillation may have shifted from their usual positions. These year-to-year variations certainly influence inter-annual temperature variability but the relations are difficult to unravel. At coastal stations, for example, anomalous frequencies of off-water flows would have a significant effect on mean annual temperature but there might be concurrent anomalies in cloudiness and in frequencies of air mass types.

The variability of the 1000-500 mb thickness field has been studied by Boer and Higuchi (1980; 1981) for the area from 25°N to the North Pole. There has been no significant change in annually-computed variance over the years 1949-1975, although there has been an increase during the summer months (June-August).

2.4 Models as a tool in early detection of climate warming

The Earth-atmosphere climate system is complex, and the idea of an equilibrium steady-state condition is not often a useful assumption, even for very long averaging times. Anomalies such as the El Nino of 1982 with its global teleconnections occur from time to time while externalities such as solar and volcanic activity must also be considered.

Methods used to provide a first guess on the climate to be expected as a result of a 50 or 100% increase in CO_2 fall into three categories:

- Steady-state models
- Transient models
- Historical analogues

(a) Steady-state models

Several steady-state simulations of the climatic effects of increasing atmospheric CO_2 concentrations have been published. A widely quoted result is given in Fig. 2-3 (Manabe and Wetherald, 1980) which shows predicted changes in zonal mean temperatures due to a doubling of CO_2. According to this simulation, the surface

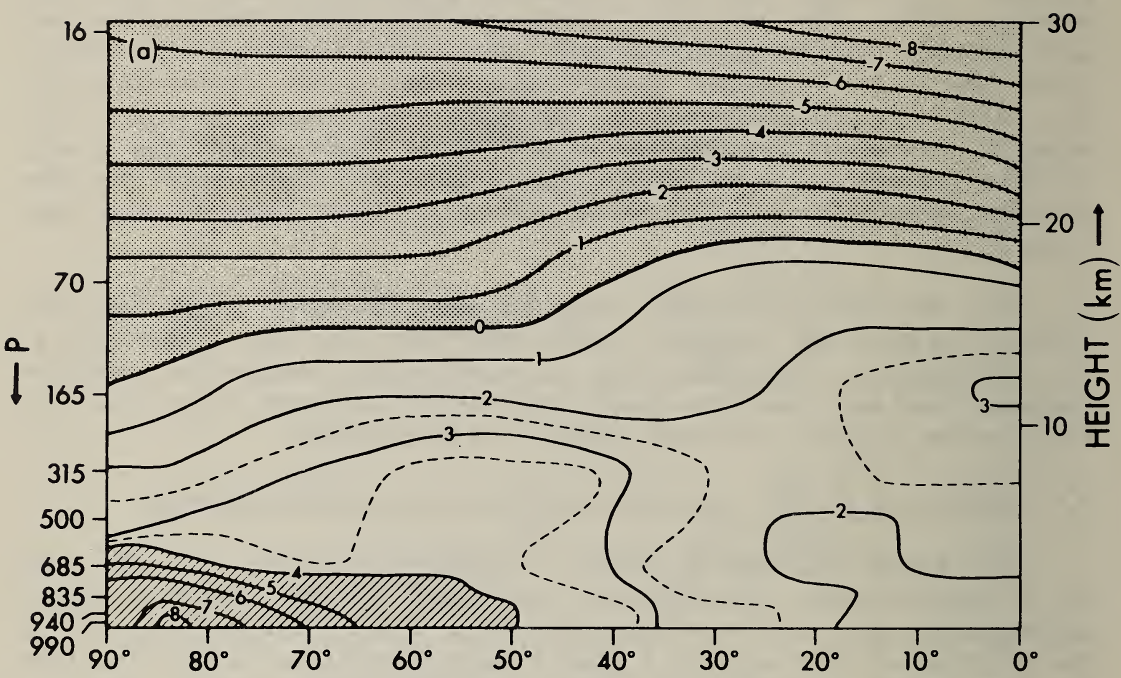

Fig. 2-3: Latitude-height distribution of the change in zonal-mean temperature (K) in response to a doubling of CO_2 content. (Manabe and Wetherald, 1980).

temperature is expected to increase by as much as 8°K in the arctic, while stratospheric temperatures are expected to decrease as much as 8°K.

Another example is given in Fig. 2-4 (Manabe and Stouffer, 1980). In this case, the surface temperature change is shown as a function of latitude and season for a quadrupling of atmospheric CO_2. In the Northern Hemisphere, the warming is greatest in the autumn and winter (up to 18°K) and smallest in July (less than 1°C). This latitudinal distribution and seasonal cycle are in agreement with the results of Vinnikov and Groisman (1982) shown in Fig. 2-5. However, the model of Ramanathan <u>et al</u>. (1979) predicts maximum warming in late spring and early summer (see Fig. 2-6), so that consensus on the seasonal cycle has not yet been achieved.[1] In this connection, it is to be noted that for steady-state models at least, there is more confidence in stratospheric than in surface predictions because latent heat processes are not involved in the former case. However, it should be added that volcanic eruptions and anthropogenic releases of chlorofluoromethanes may make stratospheric temperature trends difficult to interpret.

Additional insight into spatial patterns of surface warming is provided by a recently developed GCM model which includes ocean heat storage but no ocean heat transport (Washington, 1984). For a doubling of CO_2 concentrations, the model predicts that the greatest temperature rises would occur near sea-ice margins, particularly in winter.

(b) <u>Transient models</u>[2]

Most climate models of the effects of increasing the atmospheric CO_2 concentration have assumed "equilibrium" conditions. In these models, the CO_2 concentration is changed in a stepwise manner, e.g., instantaneously from 300 ppmv to 600 (doubling), 1200 (quadrupling), or, occasionally, 1500 ppmv. The model atmosphere responds quickly to this impulse, but the response time of the model climate is governed by the ocean because its heat capacity dominates the system. After a statistical steady state has been reached, the characteristics of the single and double (or quadruple) CO_2 climates are compared. The difference is defined as the climate change due to doubling (quadrupling) CO_2.

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1. A few individuals such as Ellsaesser (1984) question the entire climate warming scenario.

2. This subsection was written by Kerry H. Cook of the Institute for Energy Analysis, Oak Ridge, Tennessee.

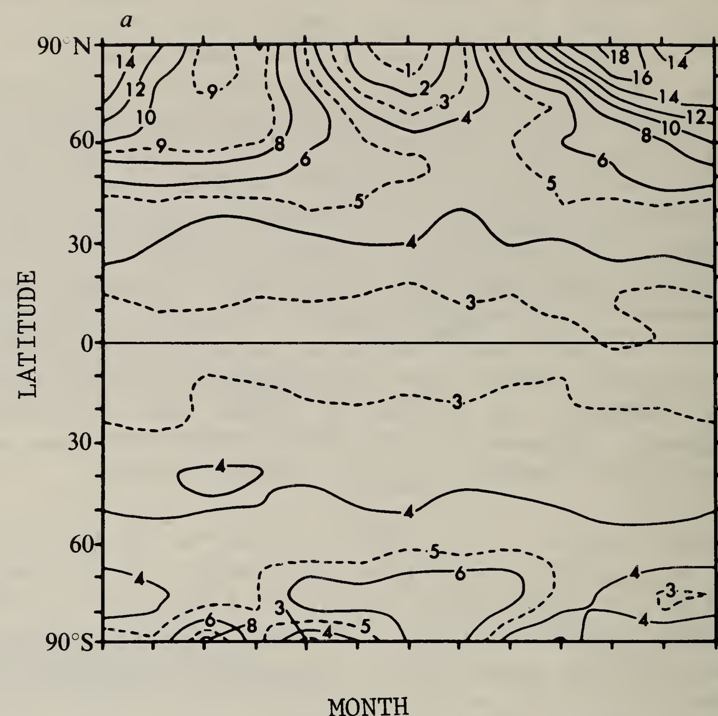

Fig. 2-4: Latitude-time distribution of zonal mean difference in surface air (70 m altitude) temperature (K) between present and quadrupled CO_2 experiements. (Manabe and Stouffer, 1979. A CO_2-climate sensitivity study with a mathematical model of the global climate. Reprinted by permission from Nature, Vol. 282, pp. 491-493. Copyright, (c) 1979, Macmillan Journals Ltd.)

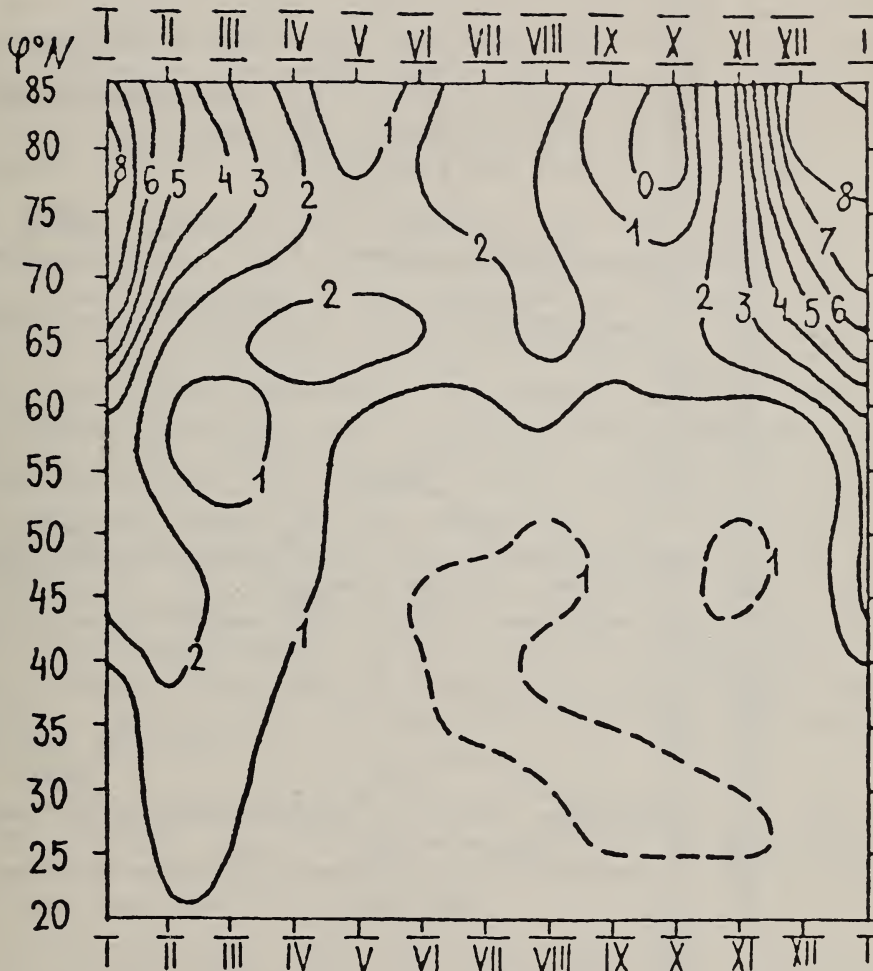

Fig. 2-5: Empirical estimate of the distribution with latitude and season of the surface temperature response function for a doubling of CO_2. This function is a dimensionless number that shows by how many times on the average the air temperature change for a given latitude and month exceeds the mean annual change for the northern hemisphere. (Vinnikov and Groisman, 1982).

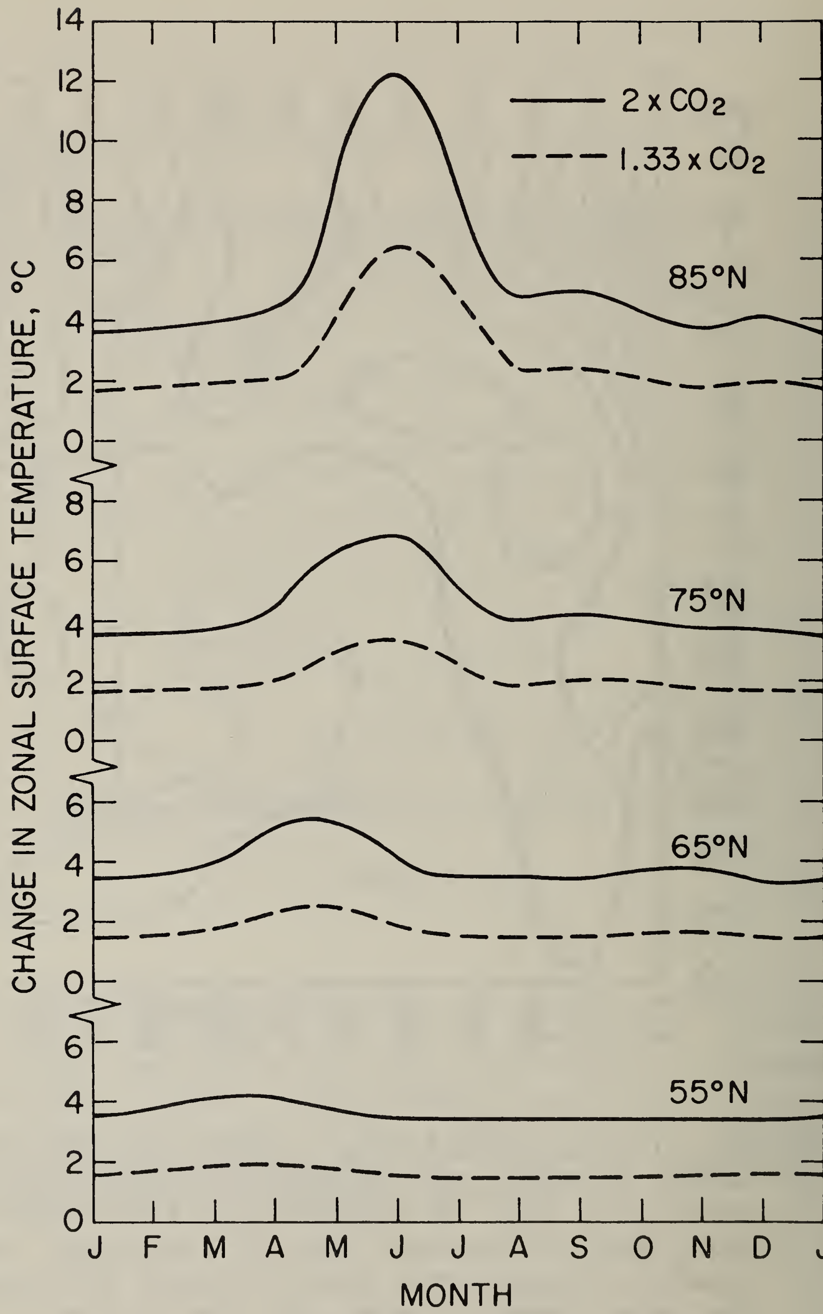

Fig. 2-6: Increase in zonal surface temperature for a number of high latitudes and for both 1.33 x CO_2 and 2 x CO_2. (Ramanathan <u>et al.</u>, 1979).

An alternate technique for investigating the CO_2-climate relationship with models is with a "transient" experiment in which the CO_2 concentration is gradually increased over decades of integration time. Computer time requirements are generally greater than for a comparable equilibrium study because the length of the integration is defined by the CO_2 increase and not by the response time of the model. However, this approach has several advantages.

The climate system is composed of many subsystems that are characterized in models by different physical processes, or even the same process operating in the presence of different external conditions. These subsystems are not independent - the magnitude and timing of one subsystem's reaction to a forcing depends on the reactions of the other subsystems. For example, consider the cryosphere and polar atmosphere as two climate subsystems, and select ice extent and lower atmospheric temperature, respectively, to represent the subsystem states. These state variables are mutually dependent and they respond to each other and, for that matter, to any stimulus with very different characteristic times. In an equilibrium experiment the climate state is sampled at, say, doubled CO_2 after both subsystems have reacted and new statistical steady states have been established. With a transient experiment, however, the climate state can be sampled as the climate passes through that state, e.g., as the increasing CO_2 concentration passes through 600 ppmv.

Another advantage of the transient experiment is that the effects of different rates of CO_2 increase can be more directly tested. For an equilibrium experiment, the way in which CO_2 increases in the real world is irrelevant.

The transient design provides a more direct test of the sensitivity of the model climate to the treatment of the ocean. Until fairly recently, the ocean was usually either included in climate models as a slave to the atmospheric temperature or held at constant temperature. More realistic consideration of the effects of the thermal properties and dynamics of the ocean is now possible. For any sensitivity study, it is necessary to include the volume of ocean water that participates in the energy balance with the atmosphere. Ocean dynamics is important in ocean mixing and in establishing the depth to which surface heat travels in the time scale of interest to the problem. For the CO_2 case, the time scale is approximately 100 years for a doubling experiment. Transient models will be useful for exploratory studies of this problem.

Transient studies simulate the CO_2 "signal" which, when combined with observed "noises", can be used to design intelligent strategies for detecting CO_2-induced changes. The transient ap-

proach provides information about time rates of change of the climate not available from the equilibrium experiments. (The approach to equilibrium has been studied in some of the more complex climate models, but is not equivalent to the true time dependence.) Results from transient models may also allow the CO_2 signal to be isolated sooner by providing a closer correlation between CO_2 concentration and climate change. With equilibrium experiments, some interpolation formula must be assumed for changes in CO_2 less than the impulsive change.

Transient model results provide information about how the climate response may lag the CO_2 forcing. The lag may be larger in some regions (and for some variables) than others. The delay may also be time dependent, so that the region with the largest equilibrium response is not necessarily the region where the response can be detected first.

Having made the case that transient models are clearly superior to steady-state ones in studies of the early detection of climate warming, it must be admitted that few results are available so far (Schneider and Thompson, 1981; Bryan et al., 1982), but a doctoral dissertation in preparation by Kerry H. Cook may provide some further insight. Intuitively, it seems likely that because of the great thermal inertia of the oceans, the air over continents would warm more than air over oceans, for a few years at least, changing the character of ocean-continent monsoons, and possibly reducing the intensity of North American east coast storm activity in autumn and winter.

A CRAY computer has recently been installed at the Canadian Meteorological Centre, Dorval and <u>it is recommended</u> that priority be given to the study of transient models of climate change on the computer.

(c) <u>Historical analogues</u>

Paleoanalogues are not very useful in the search for early indicators of climate change because paleo-records do not have a sufficiently sharp time resolution. However, an idea worth pursuing is the suggestion by Wigley (1983) that because pre-industrial CO_2 concentrations were lower than earlier believed, there must have been a considerable increase in CO_2 concentrations in the first half of this century, sufficient to explain the warming between the late 1910s and the late 1930s. (This means that other hypotheses must be invoked to account for the cooling in the 1940s and

1950s!).[3] If this line of reasoning is plausible, then climate records from representative Canadian stations for the period 1900-1940 could be used to test statistical trend detection techniques. It is in fact recommended that analyses of this type be undertaken.

3. Statistical Approaches Available for Trend Detection

3.1 General

Several statistical techniques are available for identifying and testing the significance of trends in rather noisy data sets. The first step in such an analysis is to "massage" the data (quality control; insertion of dummy values for missing observations; smoothing over time and space; etc.). To reduce the effect of year-to-year fluctuations, 5- or 10-year running mean values are often computed. To reduce spatial variability, measurements are often averaged over a hemisphere, latitude belt or a region. (Figs. 1-1 and 2-2 give examples.) In this connection, however, it is desirable to undertake analyses for each station as well as for pooled data sets. Although station-by-station statistical analyses will increase the variability in the results, some essential information is lost by spatial averaging.

3.2 The detection of trends

(a) Detecting changes in mean values

The statistical properties of a time series may change because of changes in mean value, variance, or shape of the frequency distribution. In the first case, the classical methods for identifying changes are:

- the student t test (for a step change);
- regression analysis (for a trend) (either linear, curvilinear or transformed linear).

Climatological examples of trend analysis are to be found in the papers of Angell and Korshover (1978), Boer and Higuchi (1980) and Harley (1980).

---

3. Etkins and Epstein (1982) suggest that warming in the early part of this century caused calving of the polar ice sheets. This drained latent heat from the ocean-atmosphere system, lowering surface air temperature.

A more elaborate scheme for trend detection has been proposed by Epstein (1982). For a single time series T_i, the basic model is that

$$T_i = A_i + \Delta_i + e_i$$

where

T_i is the observed climatic mean for year i,

A_i is the "natural" climatic mean for year i,

Δ_i is a possible extrinsic trend,

e_i is a random variable with zero mean uncorrelated with A_i, Δ_i or e_j.

Using global annual mean temperatures for the years 1958 to 1980, Epstein examines three possible forms for Δ_i:

- a step function increase between 1976 and 1977 (not realistic but introduced for illustrative purposes);
- exponential increase since 1958;
- exponential increase since 1973.

Using the likelihood ratio (see Epstein, 1982 pg. 1174) to test statistical significance, Epstein estimates the probabilities of detecting postulated future changes in climate. He suggests that a modest increase in global mean surface temperature should be detectable within 10 years. However, the time horizon decreases to 6 years if joint likelihood ratios are computed for surface warming and stratospheric cooling. These estimates are of the same order of magnitude as that of Madden and Ramanathan (1980).

Identification of trends in climatological series is frequently confounded by the presence of low-frequency phenomena due, for example to the Southern Oscillation, the 11-year sunspot cycle or a spell of above-normal or below-normal volcanic activity. As an example, Fig. 3-1 shows the rhythm existing in a 35-year sequence of sunspot numbers (WDC, 1981); whether this rhythm modulates any of the climatological time series remains speculative.

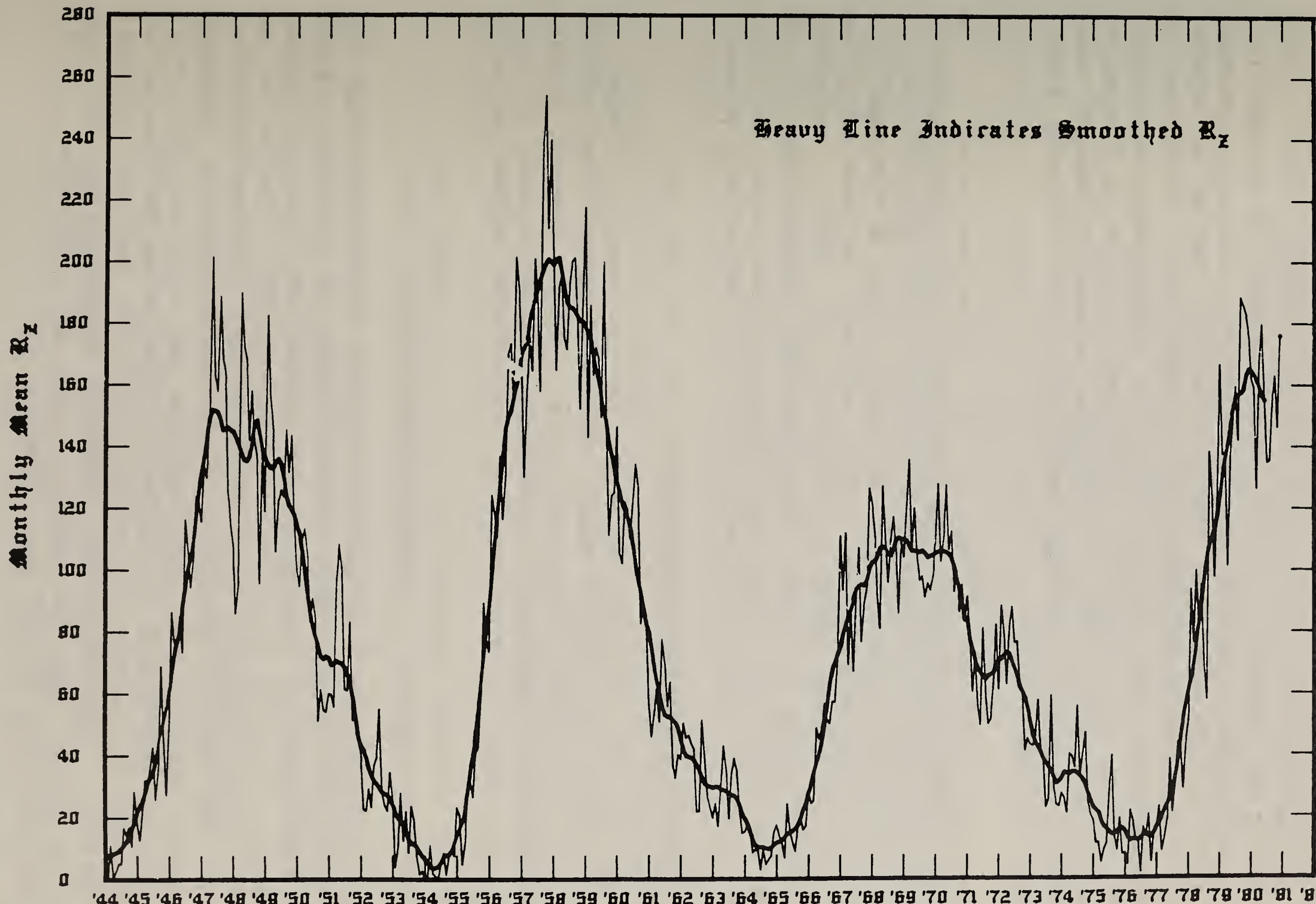

Fig. 3-1: Monthly mean Zurich sunspot numbers, January 1944-December, 1980. (WDC, 1981).

World Data Center A for Solar-Terrestrial Physics

The Box-Jenkins intervention technique is recommended for time series containing such oscillations (Box and Jenkins, 1976). Using the information included in an historical record up to some time To, the subsequent behaviour of the series is predicted and compared with the observed one. As an example, Tiao _et al_. (1974) analyzed carbon monoxide concentrations measured at 7 stations in Los Angeles County from 1955 to 1972. The authors were able to detect the effect of a change in instrument calibration procedures that occurred in April 1968. In addition, a general downward trend in concentrations was identified, although it was not quite significant at the 95% level.

The Box-Jenkins method assumes that variations/cycles in the historical time series are of unknown cause. The technique can of course be improved if deterministic cycles can be removed from the time series at the outset, e.g., the annual cycle in the case of a series of monthly mean values. This approach has been used, for example, by Gilliland (1982) and Hansen _et al_. (1981). According to Shuurmans (Crane and Bach, 1984, pg. 41), however, many of the attempts to account for solar and volcanic periodicities lack credibility, and the statistical approach is more reliable at present.

(b) _Detecting changes in variances_

Sometimes the interest is in testing for possible changes in variance rather than in the mean. The usual statistical methods apply (see, for example, Boer and Higuchi, 1980). However, because the variance of a time series is inflated by the presence of trend in the mean value, it is desirable to remove trend before beginning analysis.

(c) _Detecting changes in frequency distributions_

In some cases, the shapes of frequency distributions may undergo important modifications, although means and variances may not change significantly; histograms may become more sharply peaked, for example. In such situations, the appropriate technique to use is called _Ridit analysis_, in which the entire frequency distribution for each year or season is compared with that of a reference distribution (usually that obtained from the whole record). More specifically, the chance is estimated that a random observation from the year in question is greater than that from the reference distribution. The resulting excedence probabilities are then tested for trend. See, for example, Craig and Faulkenberry (1979) and Munn (1984, pg. 19) for more details.

(d) Estimating the length of time required to detect a trend

Statistical methods can be used to estimate, for a given confidence level, the number of years of measurements that would be required to detect a trend of given magnitude if it were to occur in the future. For example, Pittock (1972) used 16 years of total ozone data at Aspendale, Australia to obtain the results summarized in Table 3-1. At the 95 and 99% confidence levels, respectively, a trend of 2.5% per decade would require 17.5 and 21 years to detect; as the size of a trend increases, the time required to detect it decreases. A review of the methods available has been given by Munn (1984) in the acidic deposition context.

3.3 The use of signal-to-noise ratios for establishing priorities

The relative ease with which a trend can be detected depends on:

- the size of the trend;
- the variance of the time series;
- the shape of the trend line (a jagged trend line will be difficult to detect);
- the spatial coherence of the trend;
- the occurrence of trends in several related climate-change indicators;
- the degree to which the observed patterns can be explained from climate models.

The first two factors can be combined into a signal-to-noise ratio (S/N), which can be used to select from several stations/indicators, those locations/indicators best suited for trend detection.

If values of S/N are assumed to be normally distributed, then according to Klein (1982) and WCP (1982, pg. 17):

- $S/N > 1$ occurs by chance 32% of the time;
- $S/N > 2$ occurs by chance 5% of the time;
- $S/N > 3$ occurs by chance less than 1% of the time.

This provides a way of assessing the statistical significance of computed values of S/N.

Table 3-1: (Pittock, 1972)

Trend b (% decade $^{-1}$)	2.5	5	10	20
Years N, P=95%	17.5	11.0	7.0	4.5
Years N, P=99%	21.0	13.2	8.4	5.3

Number of years of observation, N, of total ozone at Aspendale necessary to determine trend levels of various magnitudes, b, at the two-sided probability levels, P, as indicated.

The noise component N is computed as the root-mean-square variability of historical data sets or of model predictions, a correction being made for the autocorrelation existing between successive members of the time series (due to trend, for example). A way of removing autocorrelation has been described by Madden and Ramanathan (1980). Based on a spectral analysis of monthly mean temperatures, the variance of the data set is calculated as a function of frequency. Then the estimated noise N is given as twice the expected standard deviation (2σ) for various averaging times. The results are shown in Fig. 3-2 for 12 surface temperature stations circling the globe at about 60^{o}N, separate curves being shown for seasonal and annual temperatures.

The signal S is estimated from model predictions or from qualitatively derived scenarios. (If a range of possible scenarios leads to rather similar selections of preferred locations/indicators, there will be greater confidence in the results.)

The most widely quoted study of signal-to-noise ratios is that of Wigley and Jones (1981), who used:

(a) the numerical simulation of Manabe and Stouffer (1980) to estimate signal in monthly mean temperature (see Fig. 2-4);

(b) temperature variance computed from the years 1941-80 to estimate noise.

The results are given in Fig. 3-3 as a function of latitude and month. Values of S/N generally greater than 10 and in some cases greater than 40 in this figure are unlikely to have occurred by chance, according to the criteria listed earlier in this subsection. Fig. 3-3 suggests that a CO_2-induced steady-state effect would be detected first in mid-latitudes in summer. This is in contrast with the behaviour of S as predicted by Manabe and Stouffer (1980) that warming would be greatest in high latitudes in autumn and winter. (See Fig. 2-4.) Although the predicted warming is not so great in summer, this factor is compensated by a decreased variance at that time of year.

Studies such as that by Wigley and Jones (1981) help in identifying areas of the globe where key indicator stations should be located -- but with three provisos:

- model predictions are rather uncertain;
- estimates of N obtained from historical time series may not be representative of future values;

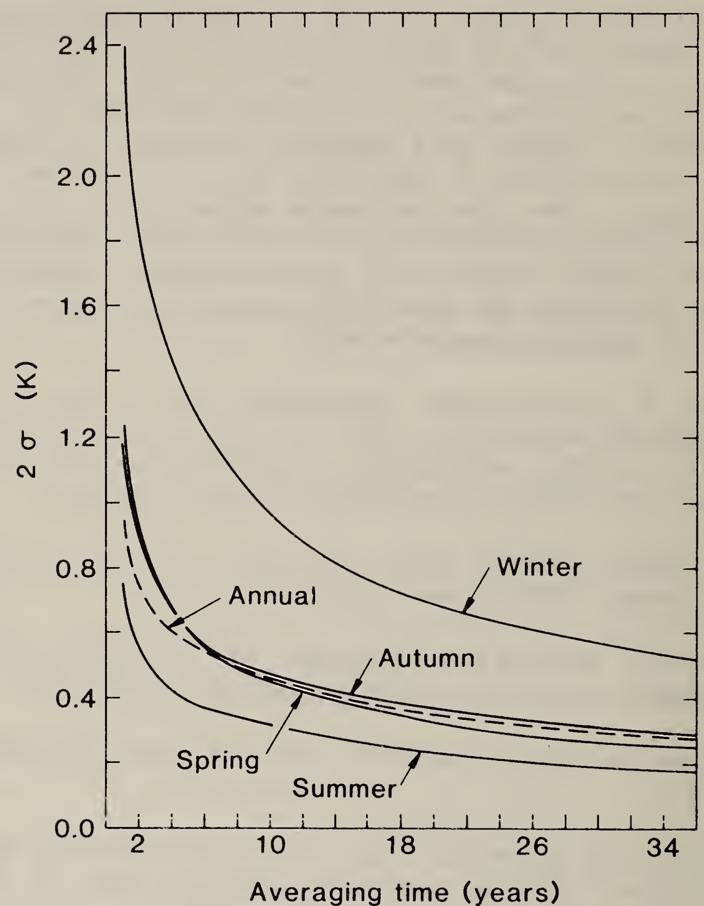

Fig. 3-2: Twice the expected standard deviations (2σ) for various averaging times for each season and for annual averages. This is the estimated noise. (Madden and Ramanathan, 1980).

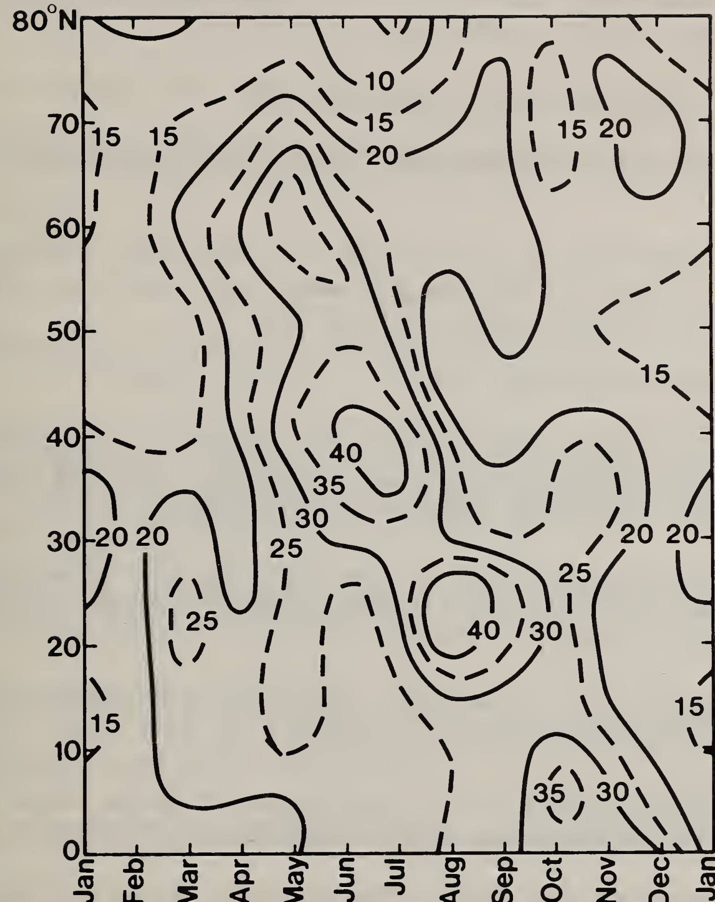

Fig. 3-3: Signal-to-noise ratio for predicted CO_2-induced changes in surface-air temperature as a function of latitude and month. The signal is based on the numerical modeling results of Manabe and Stouffer (1980). The noise has been calculated from grid-point surface-temperature data. The value for month j at latitude L is the areally weighted average of grid points at L-5, L and L+5, and the noise level is proportional to the standard deviation of month-j values over the period 1941 to 1980, corrected for autocorrelation effects. (Wigley and Jones, 1981). Reprinted by permission from Nature, Vol. 292, No. 5820, pp. 205-208, Copyright (c) 1981, Macmillan Journals Ltd.

- transitory responses to climate warming may be different than final steady-state conditions.

4. Global Indicators of Climate Change

4.1 Criteria for selecting early-detection indicators of climate change

It is important at the outset to note that several processes could cause climate change on the same time scale as CO_2 greenhouse warming. The various possibilities are:

- Increasing CO_2;

- Increasing concentrations of other greenhouse gases; (In many studies it may be convenient to pool the effects of all greenhouse gases including CO_2.)

- Oscillations over a few years in the intensity of volcanic activity and in resulting stratospheric aerosol concentrations;

- Trends in tropospheric aerosols, particularly in the arctic in winter and spring;

- Upward trends in the emissions of gases such as the chlorofluoromethanes which deplete stratospheric ozone;

- Oscillations over a few years in solar activity;

- Trends in surface albedo and emissivity due to desertification, deforestation, etc.

This spreads the net very widely, and it will be prudent to select a short list of priority early-detection indicators. Weller _et al_. (1983, pg. 333) have suggested the following selection criteria:

1. Speed of response. Does the indicator lead or lag behind other indicators?

2. Magnitude. Is the magnitude of indicator change greater or less than the magnitude of other indicators?

3. Noise level. What is the variability and bias in the indicator signal? (As mentioned in Section 3.3, magnitude and noise are usefully combined as a signal-to-noise ratio.)

4. Existence of a sufficient historical data base (including easy accessibility).

5. Spatial coverage and resolution.

For new systems, two additional criteria should be mentioned:

6. Feasibility;

7. Cost.

Finally, although not included in the list proposed by Weller at al. (1983), the following criteria would seem to be important:

8. Suitability of selected indicators for model inputs and/or outputs. Are the indicators in a form that can be used in current climate models? Can observed time series of indicator values be compared with predicted values?

9. Suitability of selected indicators to help distinguish amongst the various causes of climate change.

It is not easy to apply these criteria in an entirely objective fashion. They should, however, be considered when assigning priorities amongst candidate indicators.

4.2 Global indicators of climate change: a literature review

Three major sets of proposals for global climate-warming indicators have been made. The first by Klein (1982) is as follows, the indicators being ranked in decreasing order of priority:

1. Surface temperature, including the following derived quantities:

   a. Mean diurnal temperature range, which should decrease in dry regions;

   b. Annual range of monthly mean temperature, which should decrease in high latitudes;

   c. North-south mean temperature gradients, which should decrease;

   d. Day-to-day temperature variance, which should decrease.

2. Stratospheric temperature

Because the variance in stratospheric temperatures is an order of magnitude greater in winter than in summer, emphasis should be placed on summertime data sets. In this connection, Angell (1980) and Newell (1982) assign highest priority to trend analyses in the summer polar stratosphere.

3. Tropospheric temperature

Klein recommends that thickness rather than temperature be used as an indicator.

4. Infrared radiation, particularly:

(a) Upward radiation between 13 and 17 microns at the top of the atmosphere. This radiative flux should decrease;

(b) Downward infrared radiation from 5 to 60 microns at the surface of the earth. This radiative flux should increase.

With reference to (a), Kiehl (1983) has presented a sensitivity analysis to show that the signal received by a satellite in the 15-μm waveband due to doubled CO_2 would be about four times larger than the noise due to natural variability. The usefulness of this candidate indicator is therefore confirmed.

5. Cryosphere

The following indicators are suggested:

(a) Sea ice: extent and thickness including annual range;

(b) Snow cover; extent and annual range;

(c) Permafrost.

Emphasis should be placed on transition areas on the edges of the cryosphere.

6. Oceans

The following indicators are suggested:

(a) Sea surface temperatures including annual range;

(b) Global mean sea level.

7. Hydrological

Klein gives lowest priority to this type of indicator because of the great natural variability in elements such as cloudiness and precipitation, and because of the long chain between CO_2 warming and hydrologic effects.[4]

Klein's priority list is useful, although the selection criteria mentioned in Section 4.1 were considered only implicitly if at all.

In a second and more comprehensive treatment, Weller et al. (1983) have discussed a large number of indicators in terms of speed of response, magnitude, signal-to-noise ratio, adequacy and accessibility of historical data, and spatial coverage. The detailed discussion extends through 37 pages of text and will not be repeated here. The essential result, however, is reproduced in Table 4-1 (Weller et al.'s Table 5.11, pg. 371).

Four of the categories in Table 4-1 that do not appear on Klein's list deserve special mention:

(1) Volcanic stratospheric aerosols

The following indicators are suggested:

(a) Annual indices of the intensity of volcanic activity;

(b) Observations of stratospheric aerosol extinction;

(c) Surface actinometric data (which integrate the effects of tropospheric and stratospheric aerosols).

(2) Solar radiance

It is recommended that the solar constant (so-called) be measured routinely at the outer edge of the atmosphere.

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4. A reviewer of an early draft of this manuscript stresses that it is absolutely essential to include year-to-year variations in cloud climatologies, at least in early provisional lists of climate-change indicators. The task is technically feasible using satellite data.

Table 4-1: Priority in monitoring variables for early detection of CO_2 effects. (Weller et al., 1983)

Priority	Monitoring Causal Factors by Measuring Changes in	Monitoring Climatic Effects by Measuring Changes in
First	CO_2 concentrations Volcanic stratospheric aerosole Solar radiance	Troposphere/surface temperatures (including sea temperatures) Stratospheric temperatures Radiation fluxes at the top of the atmosphere Precipitable water content (and clouds)
Second	"Greenhouse" gases other than CO_2 Stratospheric and tropospheric ozone	Snow and sea-ice cover Polar ice-sheet mass balance Sea level

(3) Tropospheric ozone

This indicator should be included because a uniform percentage change in tropospheric ozone can have about the same effect on surface temperature as the same percentage change in stratospheric ozone.

(4) Precipitable water content

The following indicators are suggested:

(a) Precipitable water content (Models suggest that this quantity should increase by 5-15% if CO_2 concentrations doubled.) (Manabe and Stouffer, 1980; Wetherald and Manabe, 1981).

(b) Cloud amounts and types.

Appendix 2 gives a third set of proposals for global indicators of climate warming. This list was compiled by a Group of Experts during a meeting in Moscow sponsored by the WMO World Climate Programme (WCP, 1982). Brief inspection of the Appendix shows that the proposals are generally consistent with those of Weller et al. (1983), suggesting that international consensus has been achieved with respect to the selection of priority global indicators of climate change.

5. Indicators of Climate Warming in Canada

5.1 Relevance of global indicators to Canadian studies

Most of the recent interest in early detection of climate change has been on global and hemispheric scales. For example, the two major United States reports (Klein, 1972; Weller et al., 1973) have concentrated on hemispherically-averaged indicators, the implicit assumption being that regional trends are more difficult to interpret, being strongly influenced by shifts in long-wave or blocking patterns. Only in Australia has there been any attempt to study regional scenarios (Pittock and Salinger, 1982; Pittock, 1983).

Hemispheric averaging undoubtedly reduces noise levels, and Canadian climatologists should participate with other countries in global studies. In particular, the efforts of WMO-ICSU should be supported (see, for example, WCP, 1982) through the World Climate Research Programme and the World Data Centres. However, there are four advantages to a supplementary Canadian program. In the first place, homogeneity in instrumentation and observing procedures is

easier to achieve nationally than internationally. Secondly, the selection of "representative" stations can be more carefully controlled. Thirdly, some essential information is lost by hemispheric averaging; and finally, the Canadian public is interested in climate change in Canada, not in hemispheric or global averages.

5.2 Indicators of the characteristics of the general circulation in the Northern Hemisphere

Because Canada encompasses only part of the Northern Hemisphere, interpretations of climate trends can only be made in the light of year-to-year behaviour of the general circulation. Various indicators of the general circulation have been proposed; see, for example, Table 5-1, reproduced from a report of a WMO meeting on climate system monitoring (WCP, 1983a). Table 5-1 contains rather a large number of indicators, but values of quite a few of them are available from NOAA, e.g., from the NOAA "Climate Diagnostics Bulletin". (See Appendix 6 of WCP, 1983a for an example.)

With respect to adapting Table 5-1 for use in Canada, it is recommended that the Canadian Climate Centre establish a Working Group to consider the question.

It is further recommended that the Canadian Climate Centre give priority to research relating interannual variability in Canadian climate to interannual variability in the properties of the general circulation.

5.3 Canadian data sets available for studies of climate change

Table 5-2 is an inventory of types of data available for studies of climate change in Canada. Detailed listings (locations of stations, lengths of record, etc.) are available from the Canadian Climate Centre. Satellite climate information available from NOAA is given in Table 5-3 (WCP, 1983a, Appendix 10).

Within the comprehensive data banks covered by Table 5-1, only a relatively few time series will be suitable for large-scale climate change analyses.

5.4 Selection of data: spatial representativeness of the measurements

Whether the time series available for trend analysis consist of synoptic observations made at a point or whether they are line or area values (e.g., the position of the southern edge of the snow line; percentage of a water body covered by ice), a careful study of representativeness will be required. In the case of first-and

Table 5-1: Indicators of large-scale changes in the atmospheric general circulation (WCP, 1983a).

- Sea level pressure indices of the Southern Oscillation;
- The North Atlantic Oscillation and the North Pacific Oscillation;
- Zonal flow index, blocking index, trade wind index;
- Amplitude and phase of the quasi-biennial oscillation in the stratosphere;
- Various indices describing different characteristic teleconnection patterns in the middle troposphere, e.g., sea surface temperature anomalies;
- The easterly, sub-tropical and polar front jetstreams;
- Principal storm tracks;
- The tropical trade wind systems;
- The inter-tropical convergence zones;
- Principal centres of action such as the Aleutian and Icelandic lows and the sub-tropical high pressure systems.

Because climatic fluctuations in certain geographic regions often have widespread influences, anomalies over these key regions deserve special attention in any monitoring effort.

Table 5-2: Inventory of types of Canadian climate data.

(A) Available from the Canadian Climate Centre (AES, 1983)

- Weekly/monthly/seasonal/annual statistics for Canadian first- and second-order surface weather observing stations and for Northern Hemisphere upper air stations;
- Ice observations for the Arctic Ocean and Canadian inland waters;
- Background air pollution measurements from Canadian BAPMoN stations;
- Global stratospheric ozone data;
- Canadian atmospheric radiation data;
- Satellite-derived climate parameters.

(B) Available from NOAA

- Climate Diagnostics Bulletin; (See Appendix 6 of WCP, 1983a for an example.)
- Satellite information.

Table 5-3: Satellite climate information available from NOAA (WCP, 1983a, Appendix 10).

Variable	Coverage	Time Resolution	Form
Snow cover	Northern Hemisphere	Monthly	Mean snow cover map Snow cover anomaly map Frequency of snow cover map (weeks) Total snow cover area: a) N.H., b) N. America c) Eurasia Time series area of snow cover anomaly; a) N.H., b) N. America, c) Eurasia.
Sea ice	Global	Weekly Monthly	Maps Time series sea ice area anomaly
Sea surface temperature	Global	Monthly	Isotherm map
Vegetation index (experimental)	Global	Weekly	Grey scale map
Radiation budget	Global	Monthly Quarterly	Isopleth maps - means and anomalies
- - - -			
Longwave flux, Albedo, Net radiation	Estimates from narrow spectral band observations		Zonal files, global averages
Clouds	Global	Monthly	Isopleth maps of total, low, middle and high cloud amounts

second-order weather observing stations, for example, it will be necessary to identify the stations which have not undergone significant land-use changes in the last 30 years or so and which are not likely to be affected over the next several decades. The number of such stations will be small. In 1967, M.K. Thomas proposed the following list with respect to homogeneous surface temperature records (extending over 80 years in most cases):

<u>British Columbia</u>

Agassiz

<u>Yukon</u>

Dawson

<u>Alberta</u>

Banff

Indian Head, Qu'Appelle

<u>Manitoba</u>

Morden

<u>Ontario</u>

Beatrice, Orillia, Parry Sound,

Pelee Island, Southampton

<u>Quebec</u>

Father Point

<u>Nova Scotia</u>

Sable Island, Yarmouth

<u>Newfoundland</u>

Belle Isle

This list is useful but it needs to be updated, through careful examination of station records and discussions with regional meteorological inspectors. Once the subset of representative stations has been identified, additional quality controls should be

given to the data sets, appropriate statistics should be calculated, and ready access should be provided through computer tapes, etc.

5.5 Selection of data: temporal representativeness of the measurements

Because standard weather observations are made at regular intervals, temporal representativeness is assured. For other climate-related indicators such as snow and ice cover and stratospheric ozone, this question needs special consideration, and it is recommended that a study be undertaken for each indicator selected. For example, because Dobson observations of total ozone can only be made when the sun is shining, monthly mean values may be biased in some way.

5.6 Priority indicators

The following priority list of climate indicators is proposed. Unless otherwise specified, annual mean values should be used, together with summer (April-September) and winter (October-March) values. Because the models disagree on whether warming will be greatest in summer (Ramanathan *et al.*, 1979) or winter (Manabe and Stouffer, 1980), it is desirable to include both cases.

1. Surface temperature

- Mean values (by year and by season of each year)
- Mean diurnal temperature range (by year and by season of each year)
- Annual range in mean monthly temperatures (by year)
- Variance in mean daily temperatures (by year and by season in each year)
- Variance in seasonal and annual mean temperature

2. Upper-air temperature

- Mean 850 mb to 700 mb thicknesses (by year and by season of each year).
- Mean 500 mb to 300 mb thicknesses (by year and by season of each year).

- Mean 850 mb to 150 mb thicknesses (by year and by season). (By combinging the expected tropospheric warming and stratospheric cooling trends, the strength of the signal would be increased.)

3. <u>Radiation</u>

- Mean downward short-wave and long-wave radiation at the surface of the earth during clear skies (by year and by season of each year). (Implementation will require a feasibility study to develop data-selection and averaging procedures.)

4. <u>Cryosphere</u>

- Sea and fresh-water ice (maximum and minimum seasonal extents; mean thickness)

- Snow cover (seasonal southward extent) (Implementation will require feasibility studies.)

- Annual glacial advances or retreats.

5. <u>Aerosol extinction</u>

- Clear-sky actinometric observations (See WCP, 1982, for example.)

- Clear-sky BaPMoN turbidity measurements.

6. <u>Water temperature in the Bay of Fundy</u>

Bell (1982) has suggested water temperature of the well-mixed Bay of Fundy as a climate-change indicator. (The variability would be much less than that of an air temperature record from a land station but the lag might be increased to an unacceptable level.) (Implementation would require a feasibility study.)

Other indicators of climate change have been considered but are not on the priority list, for one of the following reasons:

(1) The indicators have long time lags, even though they may be excellent long-term integrators of climate change. (In this category are measurements of sea-level heights, glacial volume, permafrost distributions and sub-arctic bog temperatures. Lettau (1966), for example, recommended the use of bogs.)

(2) Signal variability is very great in space and/or time. Examples of this type of indicator are cloudiness, precipitation, dates of spring break-up of rivers and of autumn freeze-ups, and soil moisture.

5.7 Arctic haze: a complicating factor

Haze has been increasing over the last 30 years in the Canadian arctic, particularly in the spring. Fig. 5-1 (Barrie et al., 1984), for example, shows mean conductivity of a glacial ice core from Ellesmere Island as a function of time from 1912 to 1980; for this part of Canada, conductivity is highly correlated with hydrogen ion concentration and thus with atmospheric sulphate and nitrate concentrations. The 1912 peak is believed to be due to the Katmau volcanic eruption of June 1912. The other feature of Fig. 5-1 is the steady rise in conductivity since the early 1950s due to the import of increasing amounts of pollutants from industrialized regions. Partial confirmation of this rise is given by a study of Polavarapu (1984) who found upward trends in atmospheric turbidity at Resolute over the years 1969-1980 inclusive.

The intrusion of haze into the arctic is episodic, the frequency of episodes increasing during the winter to reach a spring maximum. In terms of climate change, the significance is that present springtime cloud-free aerosol heating rates of the arctic troposphere could be as much as that due to a doubling of CO_2 concentrations at high latitudes (Porch and MacCracken, 1982).

6. The Utility of Existing Canadian Monitoring Systems for Early Detection of Climate Warming

Given a list of priority indicators of climate change (see Section 5), there remains the question of selecting areas of the country where change is likely to be detected first.

To begin, a search for representative stations has to be carried out with respect to each indicator. In this connection, a feasibility study should be undertaken to estimate the minimum historical data set that is tolerable for calculating noise N. For example, the variance of annual mean temperature at Beatrice could be plotted as a function of the number of years of data used to see if any reasonable cut-off could be made. In this connection, a second feasibility study should be carried out to determine whether the value of N in a relatively warm decade is significantly different from that in a relatively cold decade. If N is likely to change as climate warming proceeds, then the S/N method of assigning priorities will give very uncertain results.

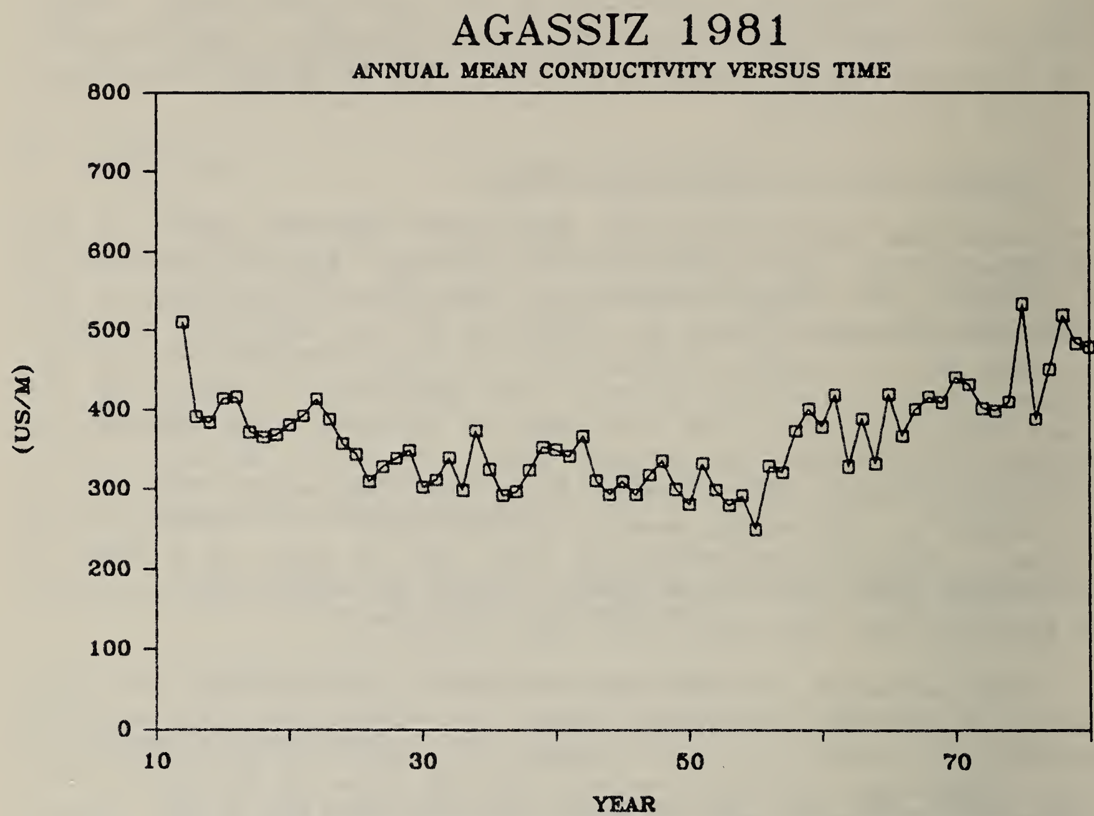

Fig. 5-1: The temporal variation of the annual mean conductivity of snow at Agassiz Ice Cap, Ellesmere Island. From 1981 ice core observations. (Barrie et al., 1984).

Next, a climate-change signal has to be postulated, either from model predictions or from subjectively derived scenarios. Given estimates of both S and N, the resulting S/N ratios should be calculated and plotted on a map of Canada, hopefully permitting the construction of isopleths (perhaps after a smoothing function has been introduced). Areas with high values of S/N would be preferred for climate change studies. This strategy would of course be modified in special cases, e.g., with respect to changes in the mean diurnal range of temperature, where a subset of days with clear skies was desirable.

Particularly with respect to the arctic and subarctic, it would be highly desirable if stations with 30 to 40 year lengths of record could be included in the "representative" category. In this connection, however, the increase mentioned in Section 5.7 in arctic haze during this same period must not be overlooked. Because spring-time temperatures are most likely to be affected by such trends, this period of the year should be excluded when searching for a CO_2-induced effect.

In summary, it is still too early to select an optimal subset of trend indicator stations for each of the priority items given in the previous sections.

7. Estimating the Lengths of Record Required to Detect Climate Trends in Canada

Finally there is the question of obtaining an early estimate of the length of record required to detect (with 95% confidence, say) a trend of given magnitude. The groundwork for this task has been laid in Section 3.2 and need not be repeated here. Using an historical data set, e.g., of temperature during the period of climate warming from 1900-1940, the number of years of record required to detect the change can be estimated by trial and error for several confidence levels. Alternatively, successive members of a steady-state time series can be increased by given amounts after some time To, and the length of time required to detect this change can be determined empirically for different trend lines.

8. Recommendations and Conclusions

The early detection of climate change is a scientifically interesting problem as well as being of considerable practical importance. Many weather-sensitive sectors of the Canadian economy are optimal with respect to current climate conditions. If climate change is imminent, Canadians will therefore need to know as early as possible.

8.1 General recommendations

8.1.1 Canada should continue to support the WMO-ICSU World Climate Programme, the World Data Centres and the WMO BaPMoN monitoring program. In particular, Canada should support the following proposals of the Joint Scientific Committee of the World Climate Research Programme (JSC, 1983, pg. 11):

- to encourage interested research groups to design and carry out numerical experiments with climate models, in order to assess the sensitivity to given changes of forcing factors (e.g., CO_2, volcanic aerosol, other trace gases). Such studies are needed to provide information for identifying indices of climate change that could yield large signal-to-noise ratios.

- to urge interested national institutions and research groups to help improve the data base for temperature measurements from land and ocean stations. Every effort should be made to ensure that the data from these different sources are homogeneous.

- to encourage efforts for a proper evaluation of the global mean air temperature from the combined land and ocean records taking into account the recently assembled Historical Sea Surface Temperature Data set, and to determine to what extent previous diagnostic studies should be revised in the light of the additional data from mobile ships.

8.1.2 In addition to the global effort, studies of Canadian indicators of climate change should be undertaken in the ways suggested below.

8.2 Priority indicators

The following priority types of indicators are recommended: surface, tropospheric and stratospheric temperatures and thicknesses; downward short-wave and infrared radiation; cryosphere indicators; aerosol extinction; and water temperature in the Bay of Fundy.

8.3 Indicators of the characteristics of the general circulation

It is recommended that the Canadian Climate Centre establish a Working Group to develop a set of indicators of the characteristics of the general circulation in the Northern Hemisphere. (See Section 5.2.)

8.4 Representativeness and homogeneity

8.4.1 It is recommended that a careful study be made of the representativeness and homogeneity of Canadian weather observing stations, through examination of station records and discussions with regional meteorological inspectors. (See Section 5.4.)

8.4.2 Arctic and subarctic stations should not be overlooked as candidates for trend analysis. It will, however, be necessary first to examine variance as a function of length of record for observing stations in several climatic zones, the objective being to determine empirically the number of years of observations required in order to get a stable estimate of the variance.

8.4.3 Once the subset of homogeneous Canadian stations has been identified, the data sets should be given additional quality controls, appropriate statistics should be calculated, and ready access should be provided through computer tapes, etc.

8.5 Statistical approaches to trend detection

8.5.1 The Box-Jenkins intervention technique is recommended for trend detection (See Section 3.2.) but other methods should also be used, e.g., the Epstein likelihood ratio. Agreement amongst the results would be a good sign.

8.5.2 Climate records for the period 1900-1940 should be used to test statistical trend detection techniques. (See Section 2.4.)

8.5.3 The signal-to-noise ratio approach is recommended for establishing priorities amongst different kinds of indicators or amongst a number of monitoring sites. (See Section 3.3.)

8.6 Research

8.6.1 It is recommended that priority be given to research relating interannual variability in Canadian climate to interannual variability in the properties of the general circulation. (See Section 5.2.)

8.6.2 It is recommended that for representative stations identified under 8.4.1 with records dating back to 1900, the 1900-1940 warming period be used for trend detection tests.

8.6.3 It is recommended that priority be given to the study of transient models of climate change on the CRAY computer at CMC Dorval.

In conclusion, it must be noted that the selection criteria for priority elements/stations mentioned in Section 4.1 have not been applied very objectively in this report. This is mainly because of the need for various pre-programming activities (such as a review of the representativeness and homogeneity of Canadian climate stations and data) before an optimal program can be designed. So the recommendations that have been made are provisional, and it seems appropriate to recommend that a follow-up Workshop be held in late 1985 or 1986.

Acknowledgements

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Appendix 1

Elements constituting "climate data" (WCP, 1983a)

The elements considered to be directly relevant to the earth-ocean-cryosphere-atmosphere climate system, are the following:

Upper air: pressure, temperature, wind direction/speed, humidity/moisture profiles; upper-air circulation patterns.

Surface terrestrial: precipitation (liquid and snow), temperature, max/min temperature, pressure, wind speed/direction, cloudiness, evaporation, snow (coverage, type, depth/water content), moisture/humidity, sunshine duration, net radiation. Also included are hail, frost, thunderstorms, severe weather, gales and gusts, sand storms and maximum wind speeds.

Ocean surface and sub-surface: surface winds, sea surface temperature, air-sea temperature differences, heat content, temperature and salinity profiles, sea level, near surface currents, deep ocean circulation, velocity profiles, evaporation, precipitation, pollution by chemicals, oil and petroleum products.

Cryosphere: glaciers and continental ice sheets - size, elevation, movement; ice sheet boundaries, sea-ice boundaries, sea-ice coverage, thickness, melting and drift; snow cover and water content.

Radiation budget: related data on clouds (radiation effect) - cover, type height, thickness/optical depth; planetary radiation budget components, solar constant, solar UV flux, surface albedo, surface radiation, net solar and IR radiation of the surface, land and ice surface temperature.

Atmospheric composition: CO_2, O_3 and other radiatively active gases, N_2O, CFMs, CH4, trace gases, stratospheric H_2O and aerosol, tropospheric aerosol, turbidity, pollution, air and precipitation chemistry.

Hydrosphere: surface water (rivers, lakes, reservoirs - stage, run-off, streamflow, sediment transport/deposition, temperature and physical and chemical properties of water, characteristics and extent of ice cover). Ground water (water table, temperature, physical/chemical properties of water).

Land and vegetation: water run-off, evaporation/evapotranspiration, plant water stress, soil temperature/moisture of the surface and at various depths, vegetation cover and changes, phenological data, soil type and changes.

Proxy data: proxy climate data derived from a wide range of biological, geological and geophysical phenomena; ice-cover ocean cores (micro-fauna and isotopes), tree rings, lake varves, pollen records.

Solar data: sun spots and flares, alpha particles, solar magnetic fields.

Appendix 2

Measurements needed for early identification of climate change, as suggested by the World Climate Programme (WCP, 1982).

Measurement	Purpose or rationale	Status of Method
a. Surface air temperature from land station network and free air temperatures from radiosonde (rawin) station network.	Temperatures are directly affected by the radiation balance of the atmosphere, and hence respond to CO_2 increases. Models indicate that surface warming will be accompanied by cooling in statosphere, and that polar surface air temperature changes will be larger than equatorial.	Routine by World Weather Watch network.
b. Sea surface temperature and surface air temperature over the oceans.	The response of the upper layer of the ocean is an important aspect of global warming; air temperature over oceans needed for obtaining a representative average.	Routine, but data collection and dissemination requires improvement, especially air temperatures.
c. Global concentration of carbon dioxide.	A major potential climate forcing factor.	Routine; continuous sampling at a few stations.
d. Global concentrations of other long-lived minor trace gases (O_3, CFMs, CH_4, H_2O, etc.)	Another potentially large climate forcing factor that could reinforce the CO_2 greenhouse effect.	Continuing special efforts; direct sampling and spectral absorption.
e. Concentration and distribution of stratospheric aerosols, especially following large volcanic eruptions.	Stratospheric aerosols from major volcanic eruptions attenuate sunlight, cause surface cooling and of stratospheric warming.	Continuing special efforts; aircraft, surface-based lidar, satellites.

f. Atmospheric turbidity distribution.	A measure of the total attenuation of the direct solar beam indicating total aerosol burden in troposphere and stratosphere.	Routine; actinometric network needs to be extended to tropics and southern hemisphere and complemented with meteorological data.
g. Total solar flux at the top of the atmosphere combined with continued ground-based observations of solar phenomena, e.g., sunspots, solar flares, solar diameter.	Present indications are that solar irradiance is not constant, and changes in solar heating are a potentially large climate forcing function. Such changes should be correlated with ground-based observations of solar features.	Special effort required from satellites for solar flux measurements to fraction of 1%.

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